APPLICATION NOTE

CAR IGNITION WITH IGBTS

by M. Melito

ABSTRACT

IGBTs are used in a variety of switching applications thanks to their attractive characteristics, particularly their peak current capability, ruggedness and simple gate drive requirements. Until recently their use was limited to the electrical drive sector, where they were required to be fast like Power MOSFETs and to have low conduction losses like BJTs.

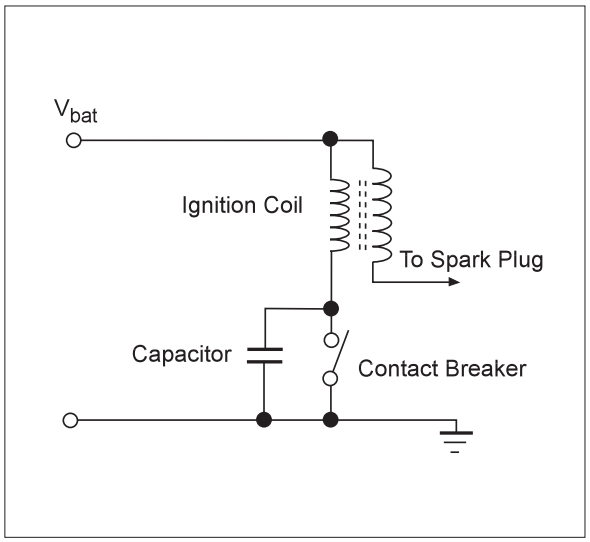
As automotive ignition switches operate at low frequencies, they are not required to be very fast. However they must have very low $V_{CE(sat)}$, and be very rugged. Existing technology allows a compromise between switching speed, ruggedness and power dissipation.

This paper gives a brief explanation of the physics and structure of the device, and highlights the characteristics which make IGBTs particularly suitable as power switches in automotive ignition systems.

1. INTRODUCTION

The inductive discharge ignition has evolved very little in its basic structure since its origin. The topology of this system using an ignition coil, contact breaker (points) and capacitor is shown in figure 1.

Figure 1: Inductive Ignition schematic



1.1 Conventional ignition systems

As the car engine rotates, the points close allowing a current to flow in the ignition coil. As the fuel-air mixture to be burnt reaches maximum compression in the cylinder, the points open, so interrupting this current and causing a large over-voltage pulse on the primary of the ignition coil. This pulse is converted by the coil to a voltage sufficient to produce arcing across the sparkplug, which ignites the fuel.

A capacitor is connected across the points to limit the rate of rise of voltage when the contacts open, so suppressing unwanted arcing which causes contact wear and reduces system output.

The performance of this type of ignition system falls significantly at high R.P.M., with low battery voltages (e.g. during starting) or with fouled plugs.

Also, even with the capacitor connected across the points some arcing does occur, causing wear and consequently timing variations. Modern inductive discharge ignition systems remove these limitations.

One of the weaknesses of the circuit of fig.1 is the points, which have a restricted current carrying capability, and limited rate of voltage rise on opening. Introduction of semiconductor components to replace these has led to significant improvements in overall performance and reliability of automotive ignition switching systems.

1.2 Electronic alternatives

If an electronic switch is used to switch the ignition coil current, then the points can be used only to switch a small non-inductive sensing current, or can even be eliminated by using more reliable electronic sensors (such as Hall-effect or magnetic).

This allows the use of a low inductance, higher peak current ignition coil, resulting in an improved performance at high R.P.M. and better firing of fouled plugs.

To further improve system reliability more modern automotive ignition systems do not use a distributor, whose function is instead performed by a specially designed ignition coil. This is the basis of the transistor assisted ignition system.

It should be noted that unless a special ignition coil is used, there is a little to be gained in performance by adding atransistor assisted ignition to an automobile.

1.3 Specification of an ignition switch

An automotive ignition switch must meet certain specifications concerning voltage and current rates, minimum energy handling capability in case of spark plug disconnection and driving requirements, over the whole temperature range.

The main requirements are related to :

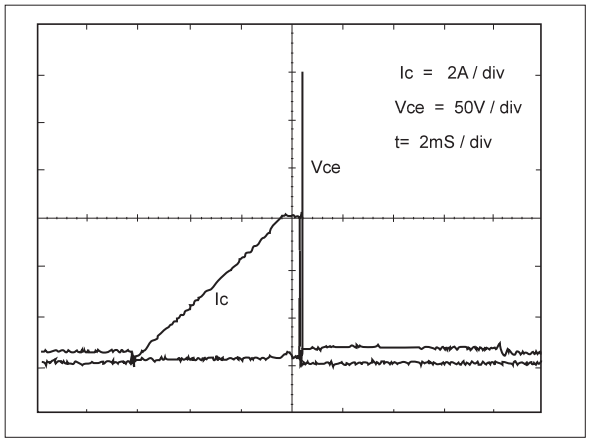
- Breakdown voltage
- Current and saturation voltage
- Safe Operating Area
- Input characteristics
- Temperature range and power dissipation.

1.3.1 Breakdown voltage

A pulse of 250-300 V on the primary side is normally easily sufficient to activate a spark. Of course the voltage peak on the spark plug will reach 20kV or more, because of the turn ratio, before the spark is actually ignited.

Immediately after this pulse both the primary and secondary voltages collapse, and during the spark they remain significantly lower than the peak (fig.2). Consequently the protecting Zener can not be made to operate below 350V, to ensure that the voltage pulse will be high enough.

Figure 2: I_C, V_{CE} Waveforms



The switch breakdown, which must be never exceeded, must therefore be specified at least 50 V higher than the Zener breakdown to give a reasonable safe margin. Currently IGBTs are available covering a range of BV_{CES} from 400V to 1500V.

1.3.2 Current and saturation voltage

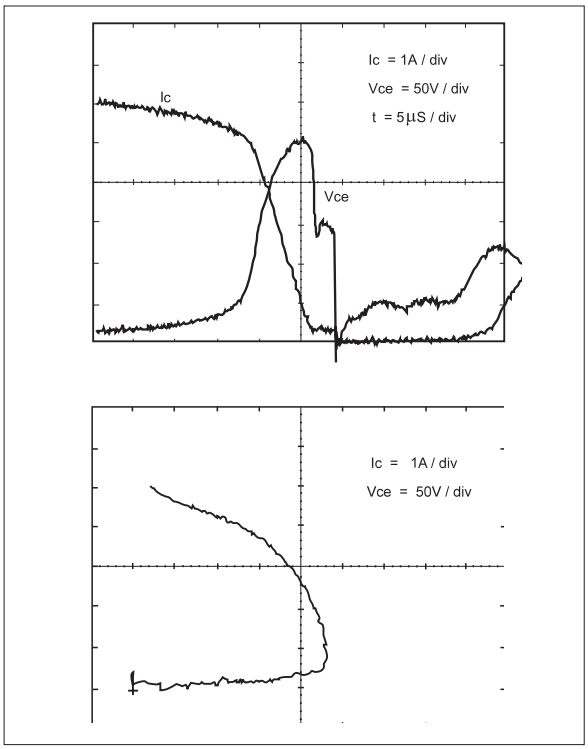
The maximum permissible current density of an IGBT rated at 500V and 8A is up to twice that of a bipolar transistor with comparable ratings, in terms not only of breakdown and saturation voltage, but also in terms of Safe Operating Area. Consequently it is possible to achieve the same performance as a standard ignition Darlington with a smaller silicon area (and hence lower cost), or alternatively to have a better thermal resistance.

1.3.3 Safe Operating Area

The Safe Operating Area describes the capability of a transistor to withstand high levels of voltage and current at the same time. There are two main conditions that would subject an ignition switch to this combined stress:

a) In normal operating condition the falling edge of the collector current during turn-off causes the collector voltage to rise until the spark occurs (fig. 3a,3b). During this phase the ignition switch must withstand high

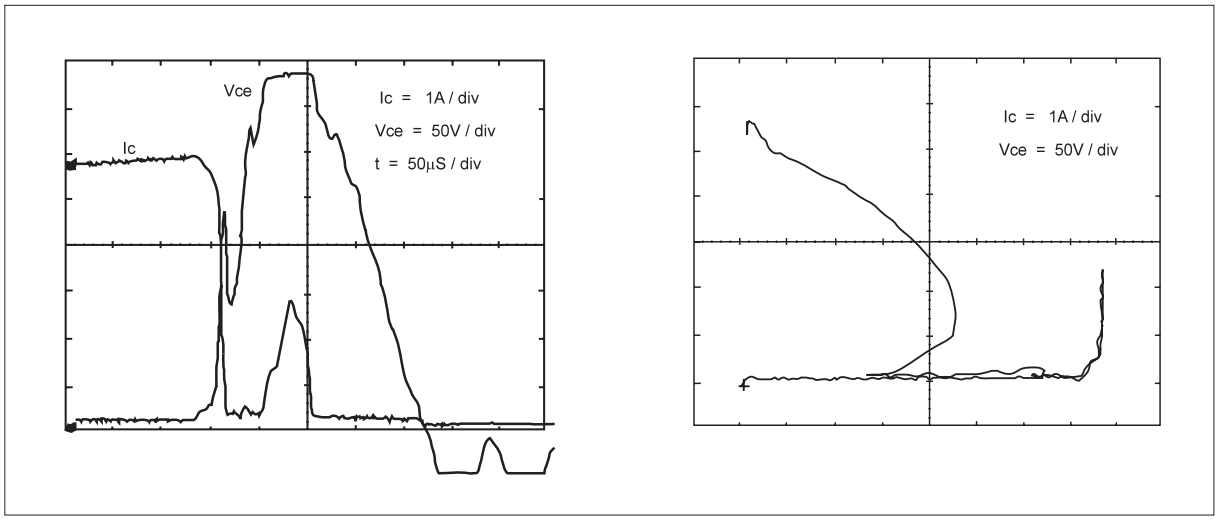
Figure 3: a) I_C, V_{CE} waveforms during spark
b) Load line during spark



voltage and current levels simultaneously, without damage or degradation of reliability. This can be achieved only if the voltage and current levels are within the boundaries of the guaranteed turn-off (Reverse Bias) Safe Operating Area (RBSOA); otherwise an aid network is required to shape the voltage and current waveforms. Current technology allows the production of IGBTs with a square RBSOA whose voltage boundary is the BV_{CES}, and whose current limit is at least twice the nominal current of the device; thus an aid network is not needed.

b) In the case of disconnection of a spark plug, the ignition switch must be able to absorb the energy that the coil is unable to release in the generation of the spark. All of the stored electromagnetic energy tends to concentrate across circuit parasitic capacitances, charging them to high voltages and putting the device in avalanche, with a risk of going into second breakdown and failing. This problem is overcome by dissipating this energy on the power switch through a protection Zener placed between the collector and the base of the device, which turns the device on as soon as the collector voltage exceeds the nominal Zener voltage (fig. 4a,4b). The usual way to indicate the minimum energy the switch can absorb without damage is to specify the battery voltage, the coil inductance and coil current,

Figure 4: a) I_C, V_{CE} waveforms in case of spark plug disconnection.
b) Load line in case of spark plug disconnection



the clamp voltage for the Zener and, if present, the collector-to-emitter capacitance. With a reasonable margin for the current, e.g. 8A, the switch must survive the switch-off without load on the coil secondary side.

A battery voltage to the upper limit of its range would be the worst case, as the energy to dissipate is :

$$E = 0.5 * L_{coil} * I^2_{coil} * \frac{V_{cl}}{V_{cl} - V_b}$$

The worst case I_{coil} will also be specified, and L_{coil} at its maximum possible value:

$$I_{coil} = 8A$$

$$L_{coil} = 7mH$$

$$V_b = 14V$$

Considering a clamping voltage of 400V the total energy is:

E = 232mJ

This kind of specification is usually referred to as the “use test” and it can be easily guaranteed for IGBTs .

1.3.4 Input characteristics

The ignition switch must be specified to ensure that the current and voltage available from the driving stage are enough to switch it on and off under all temperature conditions. The input characteristics of IGBTs are similar to that of a MOS, and they need a very small amount of energy for switching; a driving energy that is at least two orders of magnitude less than that needed by Darlingtons. Moreover, logic level IGBTs, such as the STGP10N50L, can be turned on with a gate voltage of as little as 3V.

1.3.5 Temperature range and power dissipation

The electronic components in an automotive environment are expected to work in the so called automotive under-hood temperature range, -40°C to 100°C.

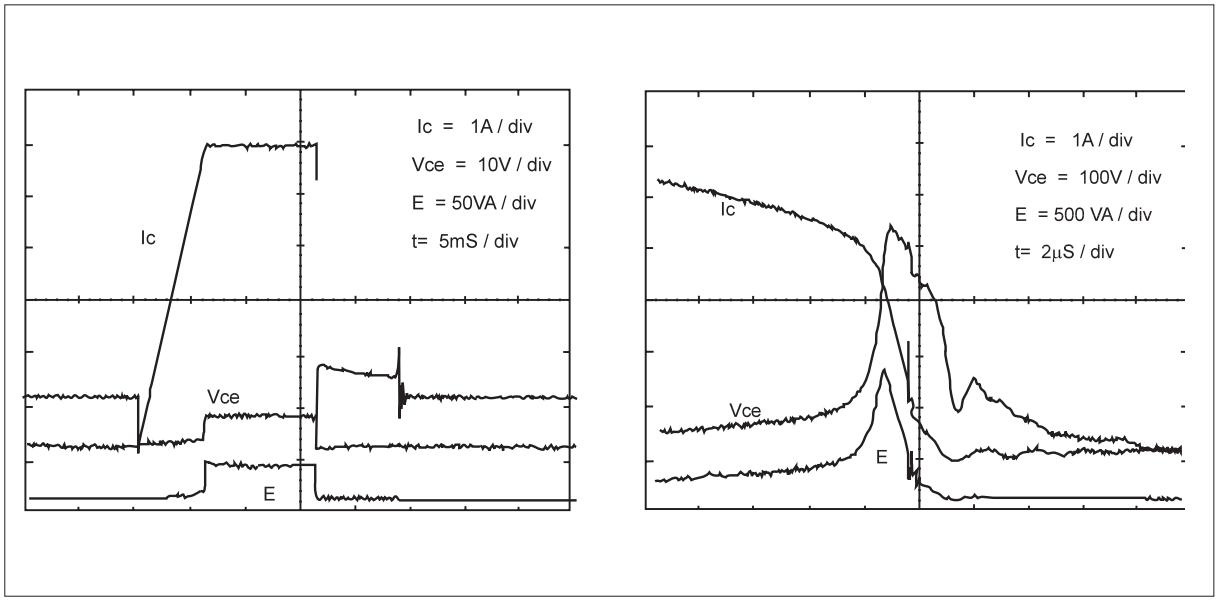
However it is preferable to specify the critical parameters not only at room temperature, but also at the junction temperature extremes of -40°C and 150°C due to the temperature increase caused by the electrical power dissipated in the device itself.

The power dissipation of an ignition switch in a high energy ignition system reaches a maximum during the current limiting interval, fig.5a, apart from a short, very high peak at the end of it due to the switch-off phase, fig.5b, and since the device is used in the linear mode the lower $V_{CE(sat)}$ has little influence in power dissipation. The junction temperature must be kept below its maximum allowable value by a heatsink whose thermal resistance must be calculated considering :

- the maximum ambient (under-hood) temperature,
- the maximum thermal resistance, junction to case, of the switch
- the thermal resistance, case to heatsink, due to the contact.

The final criterion cannot be ignored, as in some cases it can be comparable with the thermal resistance of the device itself.

Figure 5: a) I_C, V_{CE}, V*I waveforms
b) I_C, V_{CE}, V*I waveforms (expanded scale)

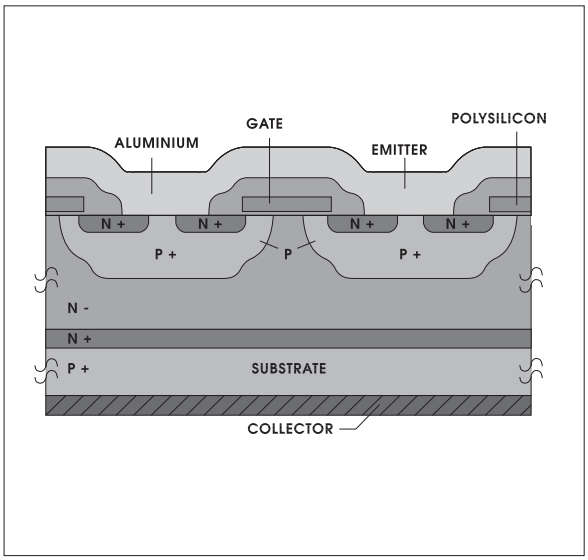


2. IGBT TECHNOLOGY AND CHARACTERISTICS

2.1 Structure

Except for the p^+ substrate, the silicon cross section of an IGBT (fig.6) is virtually identical to that of a standard Power MOSFET. Both devices have the same cellular design with p^-/p^+ body, n^+ source and polysilicon gate structure. In both devices the n^- material under the p bodies is sized in thickness and resistivity to sustain the full voltage rating of the device.

Figure 6: Basic structure of an IGBT



Although their structures are similar, the physical operation of the IGBT is very different from that of the Power MOSFET; the IGBT is a minority carrier device, and its behaviour is closer to that of bipolar transistor. This is due to the p^+ substrate which, during conduction, injects holes in the n^- region, significantly reducing its resistivity.

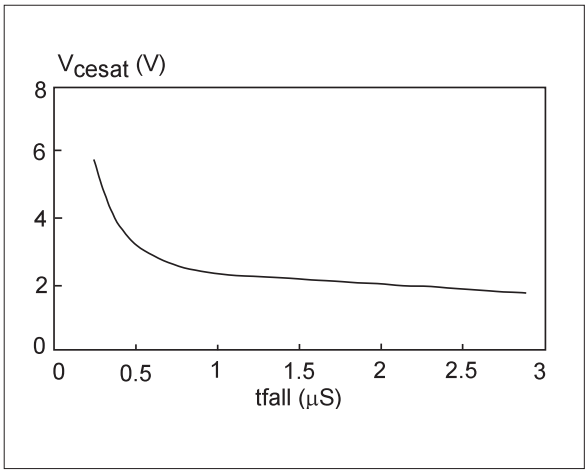
Because of the conductivity modulation, an IGBT has lower power losses than a Power MOSFET, and has a better efficiency than a bipolar transistor because the emitter covers the entire area of the die.

The switching speed of the IGBT is in general not as fast as a Power MOSFET, but this is not a limiting factor in this case because of the very low switching frequencies used in automotive ignition.

Due to the sandwiched layers of the device, the area with the extra p^+ layer forms a pnp bipolar transistor which defines the fall time of the IGBT. During turn-off the BJT portion has an open base, and switching only terminates when all the excess minority carriers within the base recombine. In a BJT, it is possible to increase the switching speed by extracting these carriers from the base, but with an IGBT it is not possible to access the base of the bipolar section. Consequently the turn-off is dominated by the lifetime of the minority carriers in the n-region.

In order to improve the fall time in IGBTs, techniques such as electron beam irradiation and doping with lifetime killers have been used to control the lifetime of minority carriers. Structural design changes, such as the insertion of a n^+ buffer layer have also been introduced (fig.6). The optimization of these techniques in IGBTs has allowed t_{fall} and $V_{CE(sat)}$ tuning (fig.7) thus allowing the best compromise between switching speed, power losses and ruggedness over a wide range of applications.

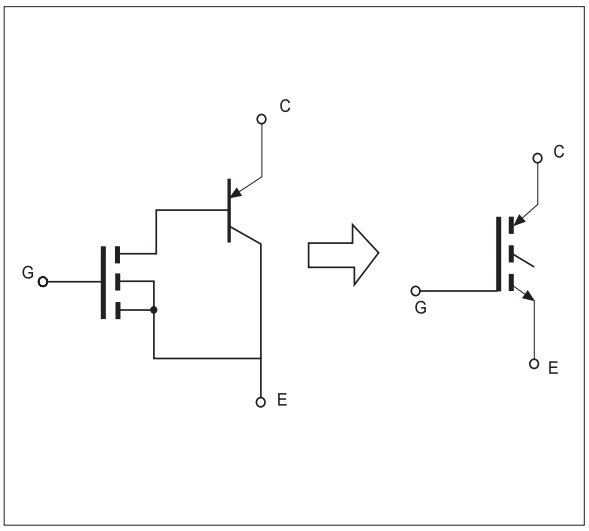
Figure 7: $V_{CE(sat)}$ versus t_{fall}



2.2 Output characteristics

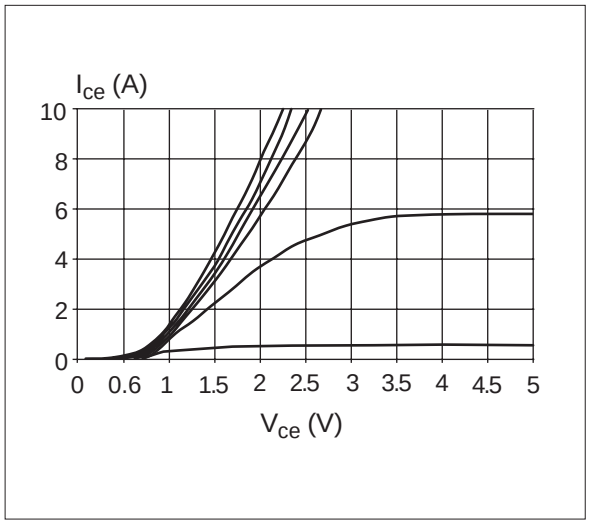
As a first order approximation the IGBT can be modelled as a pnp transistor driven by an n-channel Power MOSFET (fig.8). This model is very simple and does not take into account second order effects due to the common power MOSFET drain and BJT base region, but is useful to explain the characteristics of the IGBT.

Figure 8: Simplified equivalent circuit of IGBT, and JEDEC symbol



As is apparent from the equivalent circuit, the voltage drop across the IGBT is the sum of two components: a diode drop across the p-n junction, and the voltage drop across the driving Power MOSFET. Thus, like a Darlington, the on-state voltage drop across an IGBT never goes below a diode threshold. As the second stage of a pseudo-Darlington, the PNP is never in heavy saturation and its voltage drop is higher than that which could be obtained from the same PNP in heavy saturation. It should be noted, however, that the emitter of an IGBT covers the entire area of the die, hence its injection efficiency and conduction drop are much superior to that of a bipolar transistor of the same size. The typical output characteristics of an IGBT are given in fig.9.

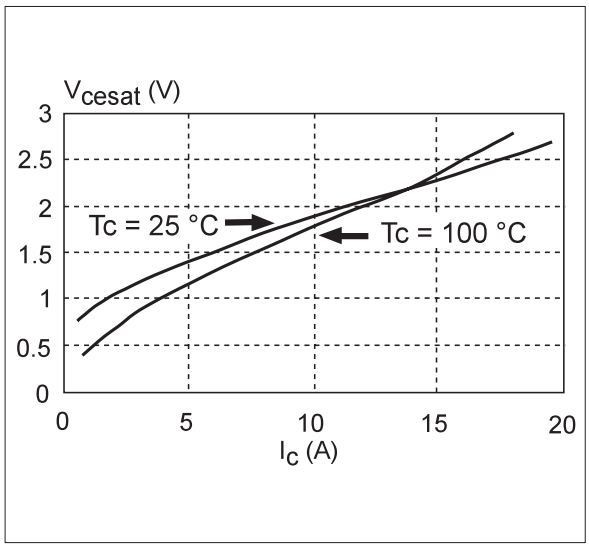
Figure 9: IGBToutput charactertistics



2.3 Temperature coefficient

The temperature coefficient of the $V_{CE(sat)}$ of an IGBT is similar to that of a bipolar transistor up to approximately $I_{C(max)}$. At this point the temperature coefficient becomes zero. At collector currents greater than $I_{C(max)}$, the temperature coefficient becomes positive and looks like that of a Power MOSFET. A typical temperature coefficient of $V_{CE(sat)}$ as a function of collector current for two junction temperatures is given in fig.10.

Figure 10: $V_{ce(sat)}$ versus I_c



2.4 Switching

Because of the similar structure, the switching behaviour of IGBTs in some aspects looks like a Power MOSFET, with the unavoidable intrinsic capacitances of the device added. In the same way the main parameters governing switching behaviour are the gate bias, the driving impedance, the gate charge and the stray inductances, but unlike the Power MOSFET the influence of the driving circuit on the current fall-time of IGBTs is negligible.

2.4.1 Turn-on

The turn-on behaviour of the IGBT is very similar to that of a Power MOSFET, and in a similar way it is possible to control the turn-on time by adjusting the gate voltage and the impedance of the driving circuit.

2.4.2 Turn-off

IGBT turn-off, shown in fig.11, can be divided into three consecutive phases:

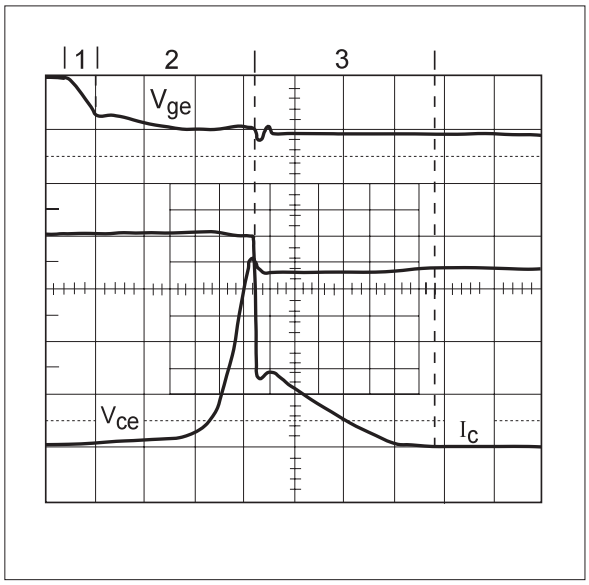
1)The gate voltage begins to decrease until it reaches the value when the Miller effect occurs; during this phase the collector voltage increases slightly changing the output characteristics with constant I_C.

2)This phase shows the Miller effect, and the gate voltage remains constant because of modulation of the collector gate capacitance. This is due to collector voltage rapidly increasing to its maximum value.

3)The collector current begins to fall quickly, and then continues with a “tail” which is due to recombination of minority carriers in the substrate.

The current tail, which causes the major part of the switching losses, is heavily related to technology, and its effect cannot be reduced by the driving circuit. The faster part of the collector current is due to the turn-off of the MOS portion of the IGBT structure. This part is connected to the PNP current gain, which, for ignition

Figure 11: IGBT turn off



devices, is designed to be relatively high to obtain a lower $V_{CE(sat)}$. The lower $V_{CE(sat)}$ is paid for with a longer current tail, see fig.7, but this price is acceptable because switching losses are negligible because of low switching frequency, compared to the losses during the on phase and during the current regulation. Moreover a very low $V_{CE(sat)}$ is important to allow the engine to start when the battery voltage is at its lower limit.

3. FUTURE IMPROVEMENTS

The structural characteristics of IGBTs lend themselves to improvements in similar ways to the developments made in Power MOSFET technology. Logic level IGBTs are available, and they can be directly interfaced to CMOS, TTL, PMOS and NMOS logic circuits, and microprocessors operated from 5V supplies. Moreover temperature sensing, current sensing, gate to emitter and collector to gate voltage clamping can be designed into IGBTs at the cost of a small increase of the silicon area and the addition of only one masking layer to the process.

The functions that can be obtained provide

significant improvement in ruggedness, reliability, protection and system cost reduction.

4. CONCLUSIONS

IGBTs are high voltage power switches which work with a very high current density. The drive simplicity coupled with excellent intrinsic ruggedness, the significant improvement in reliability, protection, system cost reduction and ruggedness improvement achievable by integrating additional functions in the same silicon make the IGBTs a very strong competitor in automotive ignition market.

REFERENCES

[1] M. Melito, “Power Switches for Automotive Ignition”,IEE Colloquium on Power Integrated Circuit, Digest no: 1989/ 34 , March 1989.

[2] M.W. Smith, “Applications of Insulated Gate Transistor”,PCI Proceedings , April 1984.

[3] D-S Kuo, J-Y Choi, D. Giandomenico, C Hu, S.P. Sapp, K.A. Sassaman and Bregar, “Modelling the turn-off characteristics of the Bipolar-MOS transistor”,IEEE Electron Device Letters, vol. EDL.6, No. 5, May 1985.

[4] R. Letor, M. Melito,”Safe behaviour of IGBTs subjected to dV/dt”

[5] A. Galluzzo,R. Letor, M. Melito,”Switching with IGBTs: how to obtain better performances”

Information furnished is believed to be accurate and reliable. However, STMicroelectronics assumes no responsibility for the consequences of use of such information nor for any infringement of patents or other rights of third parties which may result from its use. No license is granted by implication or otherwise under any patent or patent rights of STMicroelectronics. Specification mentioned in this publication are subject to change without notice. This publication supersedes and replaces all information previously supplied. STMicroelectronics products are not authorized for use as critical components in life support devices or systems without express written approval of STMicroelectronics.

The ST logo is a trademark of STMicroelectronics

© 1999 STMicroelectronics - Printed in Italy - All Rights Reserved

STMicroelectronics GROUP OF COMPANIES

Australia - Brazil - China - Finland - France - Germany - Hong Kong - India - Italy - Japan - Malaysia - Malta - Morocco - Singapore - Spain - Sweden - Switzerland - United Kingdom - U.S.A.

http://www.st.com